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Hard X-Ray Spectrometers for NIF

John Seely,[a] Christina Back[b], Richard Deslattes,[c] Lawrence Hudson,[c]
Glenn Holland,[d] Perry Bell,[b] and Michael Miller[b]

[a]Naval Research Laboratory, Space Science Division, Washington DC 20375
[b]Lawrence Livermore National Laboratory, Livermore CA 94551
[c]National Institutes of Standards and Technology, Gaithersburg MD 20899
[d]SFA Inc., 1401 McCormick Drive, Landover MD 20785

Abstract. A NIF core diagnostic instrument has been designed and will be fabricated to record x-ray spectra in the 1.1 keV to 20.1 keV energy range. The High-Energy Electronic X-Ray (HENEX) instrument has four reflection crystals with overlapping coverage of 1.1 keV to 10.9 keV and one transmission crystal covering 8.6 keV to 20.1 keV. The spectral resolving power varies from approximately 2000 at low energies to 300 at 20 keV. The spectrum produced by each crystal is recorded by a modified commercial dental x-ray CCD detector with 4000 dynamic range.

The High-Energy Electronic X-Ray (HENEX) instrument is a core diagnostic for x-ray spectroscopy at the National Ignition Facility (NIF). This instrument is designed to be a survey diagnostic that detects x-rays over a broad range of photon energies with reasonable dispersion. The dispersive elements will be Bragg crystals used in reflection or transmission, and the spectra will be recorded by CCD detectors. The instrument will obtain time-integrated data of the plasma emission. The instrument will be suitable for both the identification of plasma ion species and for absolute flux measurements of spectrally-resolved emission. In some cases, estimates of temperature or density may be possible by use of line intensity ratios, line widths, or bound-free continuum emission. Specific applications of the diagnostic will depend on the target configuration and diagnostic line-of-sight.

There are two principle ways data from this type of instrument have been used in the study of laser-produced plasmas. The relative heights and widths of spectral features can be analyzed by various spectroscopic techniques to yield information about the plasma conditions. Or, the absolute flux integrated within a spectral bandwidth can be measured to determine the total radiative energy emitted or absorbed by a target.

Spectroscopy can be an extremely powerful technique because it can be non-perturbative to the target. Dispersion of the x-rays enables the most basic application of spectroscopy: the identification of ion species present in the plasma by bound-bound emission. Many papers are devoted to the identification of lines from different ion species. These types of measurements are crucial to advancing the basic research on the atomic structure of highly-ionized plasmas.

A more sophisticated use of spectroscopy involves interpreting the spectrum with knowledge of the atomic kinetics. Emission and absorption spectroscopy can provide crucial information on the plasma conditions.[1-4] Unlike Thomson scattering, which can only probe plasma densities accessible to the probe wavelength, x-ray spectroscopy has diagnosed laser-produced plasmas with electron densities as low as 10^{18} cm^{-3} in coronal plasmas and up to near solid density in high energy density experiments. To determine plasma conditions, clever experiments can use tracer elements in the target or manipulate the diagnostic line-of-sight. These techniques enable useful spectroscopic measurements that provide localized plasma temperature or density measurements. In fact, the mere presence of a known element detected by its spectroscopic signature has been used to study mix or other hydrodynamic features of the target.[5]

Calibration of the instrument's throughput is required for absolute flux applications. The absolute sensitivity calibration is planned for the future and will be tailored for the spectral regimes of interest for applications. In indirect inertial confinement fusion experiments, a hohlraum target, expected to be an Au cylinder approximately 10 mm in length, converts laser light into x-ray radiation which implodes a capsule. Absolute flux measurements are essential to quantify the x-ray conversion efficiency. In other complex experiments that require x-ray radiography or in material testing experiments, a laser-produced plasma serves as an x-ray source. Absolute flux measurements are again needed to quantify the flux, but the spectral resolution is also necessary to tailor the x-ray sources for the particular application. Recently new types of heating have led to a series of experiments to characterize underdense plasma sources for diverse applications.[6]

The HENEX survey instrument is designed to be robust and versatile. While no single instrument can serve all the spectroscopic needs envisioned at NIF, this instrument is designed to provide enough information to identify spectral regions that may merit closer scrutiny with a higher spectral resolution and with temporal resolution. Table 1 shows the NIF specifications for the instrument. The standoff distance from the target can be from 0.5 m to 2.2 m.

Table 1. The NIF Core Diagnostic Specifications.

Photon Energy Range	1.1 keV to 20 keV
Field of View	5 mm
Minimum Spectral Resolution	$\lambda/\delta\lambda = 300$
Dynamic Range	2500
Data Acquisition	CCD

The instrument is capable of recording spectra from targets up to 5 mm in size with high spectral resolution. For applications that do not require high spectral resolution, such as the characterization of the emission from an x-ray backlighter target, the instrument can record spectra from a target within a 3 cm field of view.

As listed in Table 2, the instrument utilizes one transmission crystal (channel 1) and four reflection crystals (channels 2-5) with overlapping coverages of the x-ray energy range 1.1 keV to 20.1 keV. The transmission crystal spectrometer was originally designed at the National Institute of Standards and Technology (NIST) for the purpose of characterizing the x-ray flux from medical radiography sources.[7-9] The reflection crystal spectrometers are similar to the HENWAY instrument used at the Nova facility, but with improved crystals.[10]

An important feature of this instrument is the use of CCD detectors to facilitate data collection and analysis. The HENEX spectra are recorded on modified commercial dental x-ray CCD detectors with phosphor screens optimized for each energy range. Each CCD is 36 mm long and has an effective 40 μm pixel resolution. Furthermore, 12-bit digitization allows for a dynamic range of 4000. Based on the detector-limited resolution of 40 μm, the spectral resolving powers (listed in Table 2) are 303 to 818 for the transmission crystal and 850 to 3060 for the reflection crystals.

Table 2. Characteristics of the five HENEX crystal spectrometer channels placed 2.2 m from the NIF source. The Qz(10-10) crystal spectrometer (channel 1) is to be used in transmission and bent to a 165 mm radius of curvature; the other channels are convex reflection crystal spectrometers with a 127 mm radius of curvature.

Channel	Diffraction Crystal	Lattice Spacing (Å)	Energy Range (keV)	Bragg Angle Range (deg)	Resolving Power
1	Qz(10-10)	4.26	8.6 to 20.1	9.7 to 4.2	818 to 303
2	Qz(20-23)	1.38	7.0 to 10.9	40.1 to 24.4	3060 to 1340
3	CaF2(111)	3.15	3.6 to 7.3	32.7 to 15.6	2050 to 850
4	KDP(011)	5.10	2.2 to 4.0	34.4 to 17.5	2260 to 940
5	Mica(002)	9.92	1.1 to 2.3	33.7 to 15.7	2150 to 850

The implementation of CCD detectors enables the utilization of image processing software for the analysis of the spectral images. Once fully operational, we expect the simple quick-look analyses of spectra to become routine. For example, determining the wavelengths of spectral lines and thus verifying the identification of a backlight material in a target will be possible after each shot. Analysis of the experimental spectra in real-time is an important advance that provides the experimentalist with vital information that can affect a shot series.

The HENEX instrument is designed to be fielded in a NIF diagnostic instrument manipulator (DIM). However, it could also be modified for operation on a fixed port at the chamber wall if required. A sketch of the instrument in a ten-inch manipulator (TIM) enclosure used at the OMEGA laser facility is shown in Fig. 1. The five spectrometers are in the front end of the enclosure and the electronics box is in the back end. One reflection crystal and its CCD detector are illustrated. The two CCD detectors for the transmission crystal spectrometer are also visible, along with a diode laser used for alignment. The diode laser is mounted behind the two transmission crystal CCD detectors, and its beam passes between the two detectors, through the pinhole, and illuminates the target position. After the spectrometer is aligned, the pinhole is covered, and there is no direct line of sight from the x-ray source to the CCD detectors. The electronics box contains the computer and ethernet boards and the rechargeable batteries, which internally power the on-board electronics during the laser shot.

At the NIF laser facility, the alignment of the HENEX instrument with respect to the x-ray source is accomplished by the following procedure: The HENEX instrument mount is adjusted so that the transmission crystal spectrometer box is aligned to the DIM axis. By moving the end of the DIM in x and y, the diode laser beam is incident on the source point near the center of the NIF target chamber. The laser illumination of the source fiducial is viewed by the NIF target positioning video cameras. The DIM axial motion establishes the nominal 2.2 m standoff distance from the source. Thus the alignment is performed remotely using only DIM motions. The precision and range of the DIM motions are sufficient for good alignment of the spectrometers.

Background x-rays from the unconverted light in NIF is expected to be significant. Therefore, care was taken in designing the instrument to reduce background on the data. The front "fire-wall" plate (illustrated in Fig. 1) supports entrance aperture filters and the x-ray shielding. The CCD detectors are not directly illuminated by x-rays from the target. However, copious x-rays can fluoresce the dispersive crystals themselves and produce a significant background signal that is not spectrally resolved. Fluorescence is suppressed by using low-Z materials for the instrument structure and crystal mounts where possible. In addition, baffles permit each detector to view only its crystal and not the remainder of the instrument. Each CCD detector is covered by a filter that passes the x-ray energy band of interest and attenuates the background flux.

Furthermore, depending on the target material, it is possible that higher-order spectra may overlap the diffraction order of interest. Higher diffraction orders typically have small integrated reflectance owing to narrow rocking curves. If higher orders are of concern, they may be controlled by the use of filters that selectively attenuate the unwanted orders. It is possible to place several different filters lengthwise (in the dispersion direction) over the CCD detector, so that each filter covers a portion of the 26 mm height of the detector. The crystals are sufficiently wide so that the spectra extend across the entire 26 mm height of the baseline dental x-ray CCD detector. The spectra recorded by different filter regions of the CCD may be used to sort overlapping orders.

To the extent that it was possible to do so, we have chosen crystals that are likely to survive challenging environmental stresses and are known to survive high radiation doses. Quartz and mica are both known high-temperature materials, while the choice of KDP is based on the fact that it is the best available material with a lattice plane spacing in the neighborhood of 5 Å.

The front plate of the spectrometer also completes the Faraday cage enclosure to shield from the electromagnetic pulse and electromagnetic interference. Shielding for 14 MeV neutrons expected to be produced from fusion reactions is housed in the nosecone.

A prototype NIST transmission crystal spectrometer has been evaluated using a pulsed laboratory x-ray source developed by the Naval Research Laboratory (NRL).

A single-shot spectral image recorded on Polaroid film is shown on the right side of Fig. 2. The anode was Mo, and the peak voltage was 150 kV. The transmission crystal produces two spectra on either side of the central image of the x-ray source resulting from a pinhole in the front cover of the spectrometer. The Mo Kα and Kβ lines are visible. An enlargement of a multi-shot spectrum recorded on high-resolution DEF film is shown on the left side of Fig. 2. The Mo Kα_1 and Kα_2 lines at 17.48 keV and 17.37 keV are resolved, indicating a resolving power of approximately 300.

A single-shot spectral image recorded on Polaroid film and using a W anode with 50 kV voltage is shown in Fig. 3. The image is of the W continuum in the 12 keV to 20 keV x-ray energy range; the tungsten K-shell lines are beyond the coverage of this particular spectrometer. A one-channel transmission crystal x-ray spectrometer covering the 12 keV to 60 keV range is being fabricated for the OMEGA laser facility.

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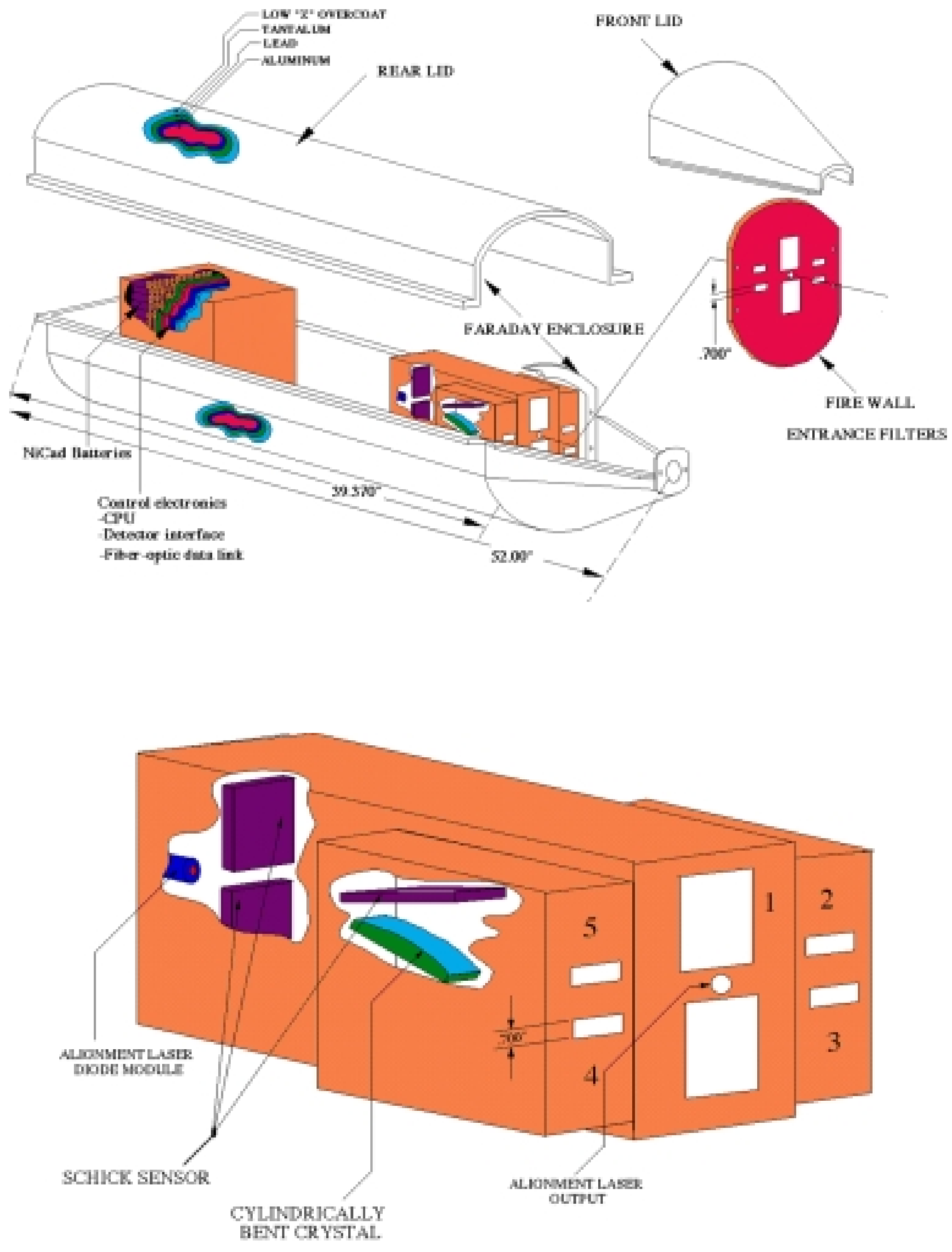

Fig. 1. Top: Sketch of the HENEX instrument in its TIM enclosure. Shown are the spectrometers in the front end and the electronics box in the back end of the enclosure. Bottom: Details of the spectrometer boxes. One reflection crystal and its CCD detector are illustrated. The two CCD detectors for the transmission crystal spectrometer are also visible.

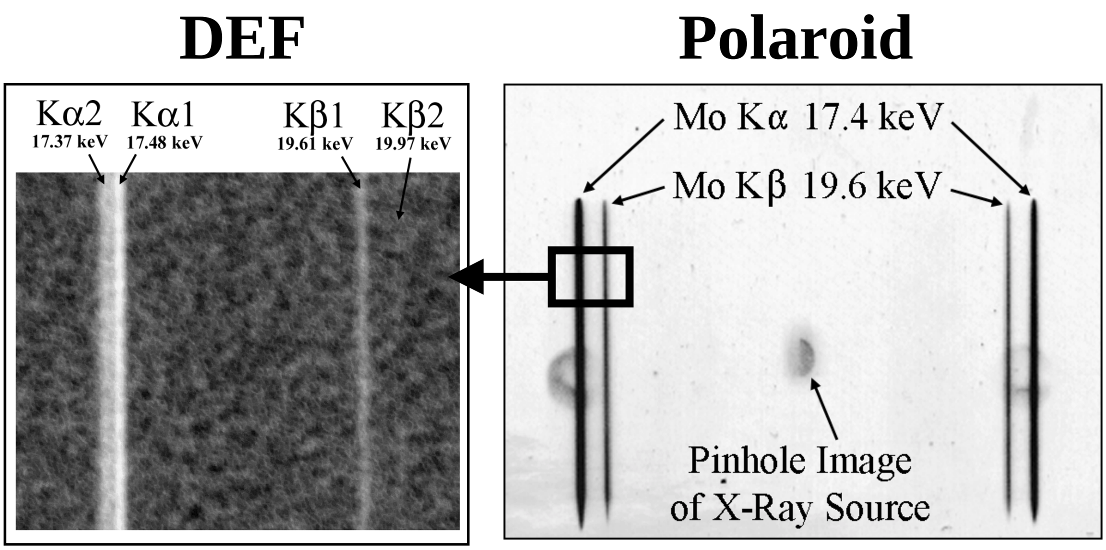

Fig. 2. Spectral images recorded using a pulsed laboratory x-ray source with a Mo anode.

Fig. 3. Spectral image recorded on Polaroid film of the continuum from the pulsed x-ray source with a W anode.